Self-Calibration and Applications of Diffraction Gratings for Precision Nanometrology

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論 文 内 容 要 旨

This paper describes not only the self-calibration method for the diffraction grating but also multi-axis optical sensors based on interference of diffraction beams as the applications of diffraction grating.

In Chapter 1, the background and the motivation of this research are presented. The diffraction gratings have widely been applied in various fields of industry. Especially, in ultra-precision manufacturing, ultra-precision positioning of the one-axis and multi-axis (X- and Y-axis) positioning stages, which are generally composed as a combination of the dual linear stages orthogonally, are most important key components to improve product quality. Moreover, in the semiconductor industry, the positioning of under several nanometers of the stages is necessary because the production process of several nanometers is required to produce the devices with a pitch of several ten nanometers manufactured over a wafer of more than several hundred millimeters. Positioning systems based on laser interference using a linear encoder with a linear scale, which is a diffraction grating with grating pitch from several micrometers to several hundred nanometers fabricated to one-axis, are widely used in manufacturing industry. The diffraction gratings can be used to determine the moved position of the stage with nanometer resolutions. On the other hand, the grating pitch should be fabricated as precise as possible to minimize period deviation over the entire area of the diffraction grating, because output of the linear encoder would be generated by processing outputs from photo detectors which capture positive and negative 1st-order diffraction beams, respectively. Generally, the diffraction gratings are fabricated in terms of lithography processes which use an interference fringe pattern from two incident beams. By adjusting the incident angle between two incident beams, the diffraction grating with a pitch of several-hundred nanometers can be fabricated on the entire area of the substrate. In case of the two-dimensional positioning, the multi-axis (X- and Y-axis) stage, which is composed by dual linear stages, is used especially in semiconductor manufacturing systems and the laser micro-processing. By applying the positioning system using the linear encoder with the one-axis diffraction grating to each linear stage, the two-dimensional positioning of the multi-axis stage would be possible. In contrast, a planar encoder, which uses two-dimensional XY-gratings, can be applied to the positioning of the planar stage. The position errors of the stages are serious issues which should be compensated accurately because it affects the positioning accuracy. To compensate the positioning errors such as X-directional positioning error and Y-and Z-directional out-of-straightness), several compensation algorithms have been proposed so far to improve the positioning

accuracy of the stage. In addition, the influences of the Z-directional out-the-flatness and X- and Y-directional period deviations of the diffraction grating must also be compensated to improve the stage positioning accuracy of several-ten nanometers because the diffraction grating generally has the Z-directional out-of-flatness and X- and Y-directional period deviations of up to several-hundred nanometers. The line scale comparator has long been used to evaluate the period deviations of one-axis linear scale gratings in national standard institutes and linear encoder manufacturers. This method is very accurate with a direct linkage to the length standard. It can provide not only the period deviations but also the absolute value of each of the scale pitches over the range of up to several meters. Measurement speed is also fast because of the using of the non-contact detection head. However, it is too expensive and complicated to expand such a system from one-axis to two-axis for the evaluation of the XY grating. Although scanning probe microscopes (SPMs) can be employed to image a small part of a planar scale grating, it is not practical to make the evaluation over the entire grating area because of the limitation of the SPM in the scanning speed and the scanning range. A laser interferometric surface profiler, which can measure smooth surfaces and plates with the vertical resolution of nanometer order, can be used for evaluating the Z-directional out-of-flatness of the diffraction grating. However, a form error of a reference mirror in the Fizeau interferometer, which is considered to be on the order of several ten nanometers, still remains as a measurement error in the form of the measured scale grating. The form error of the reference mirror should therefore be eliminated for further more precise evaluations of the grating. Although some methods have been reported, it is still difficult to acquire the form error of the reference mirror in interferometers. In addition, evaluations of vibration components of the stage are also important to enhance the performance of the positioning of the stage. Three-axis vibrations generally occur to the working table of the stage due to the mechanical unbalance. In the semiconductor industry, the detection of the three-axis vibrations of the working table, frequency range of which are from several-ten Hz to several-hundred Hz, is important to be isolated. Conventionally, single-axis displacement sensors such as a laser interferometer, a linear encoder and a capacitive sensor are assembled to construct the multi-axis displacement measurement system. Nowadays, such single-axis displacement sensors have sub-nanometric measurement resolution and sub-micrometric measurement accuracy. However, the differences of the measurement point of each displacement sensor cause Abbe offsets. In addition, the measurement system based on multiple displacement sensors often makes the whole structure large and complicated.
On the other hand, the multi-axis displacement sensors, which can measure displacements along the multiple axes simultaneously with the single measurement point, have been developed. Although the multi-axis displacement sensor is effective to prevent Abbe offset and downsize the structure of the measurement system, their abilities are not enough to satisfy the requirements mentioned above perfectly.

The motivation of this research is development of the self-calibration method for evaluate the grating errors (period deviations and out-of-flatness) of the diffraction grating to enhance the position accuracy using the optical measurement system with a diffraction grating and optical evaluation systems as the application diffraction grating. The grating errors of the diffraction grating are evaluated by processing the interference signals from not only the Z-directional zeros-order but also X- and Y-directional positive and negative first-order diffraction beams using the commercial Fizeau interferometer. In addition, measurement accuracy of the self-calibration method for diffraction grating is more accurate by compensating the form error of the reference mirror in commercial Fizeau interferometer (interferometer error). Furthermore, the novel simultaneous measurement systems as the applications of the diffraction grating are proposed in this dissertation. Firstly, the multi-axis optical interferometric vibrometer using diffraction grating to detect the 3-axis vibration components is proposed. The X- and Y-directional positive and negative first-order diffraction beams from the diffraction grating are superimposed to generate interference signals, which have information about the XY- and Z-directional displacements. The XY- and Z-directional vibrations can be measured simultaneously by processing the X- and Y-directional positive and negative first-order interference signals. The proposed multi-axis optical sensor has only a single measurement point, which contributes to the reduction of Abbe offsets. The XY- and Z-directional resolutions of the proposed multi-axis displacement sensor are determined by the wavelength of the light source and the grating period of the scale grating like the laser interferometer and the linear encoder, respectively. Next, the multi-axis mosaic encoder for the large area displacement measurement is proposed. To enlarge the measurement range, the mosaic XY grating, which can be constructed by assembling the single XY gratings to two directions, is applied to the multi-axis mosaic encoder. When the XY gratings are employed as a scale like the planar encoder, the X- and Y-directional positive and negative first-order interference signals can be obtained. As a result, the X-, Y and Z-directional displacements can be measured simultaneously by the proposed multi-axis optical sensor.

Chapter 2, the self-calibration method of the grating error (Z-directional out-of-flatness and X- and Y-directional period deviations) of the diffraction gratings for precision nanometrology is presented in this chapter. Firstly, the XY grating using in the planar encoder, which was fabricated to the X-and Y- each axis, was fabricated by applying to laser lithograph method using the laser interference over the large area (100 mm (X-axis) x 100 mm (Y-axis)). The grating pitch of 1 μm with respected to the single-axis (X-axis) was firstly fabricated. After that, the substrate was rotated 90 degrees to fabricate the grating pitch of 1 μm with respected to the another-axis (Y-axis) in the same area. The Z-directional out-of-flatness and X-directional period deviations of the fabricated XY grating were calibrated by using the commercial Fizeau interferometer. The Z-directional out-of-flatness of the XY grating over the entire area could be calibrated by analyzing the interference phase output generated by the two-beams (reference beam reflected form the reference plat and Z-directional zeros-order diffraction beam diffracted from the XY grating). On the other hand, the X- and Y-directional period deviations of the XY grating could be calibrated by processing not only the X-directional but also Y-directional positive and negative diffraction beams diffracted from the XY grating. In order to measure the X-directional positive and negative diffraction beams to calibrate the X-directional period deviation, the XY grating was rotated to counterclockwise and clockwise with respect to the X-axis by using the manual tilting stage, respectably. The Y-directional period deviation of the XY grating also can be calibrated by rotating the XY grating to measure the Y-directional positive and negative diffraction beams. The rotation angle was 22 degrees, which is half of the diffraction angle of the XY grating. Calibration results of the grating errors (Z-directional out-of-flatness and X- and Y-directional period deviations) were described in this chapter. The Z-directional out-of-flatness of the XY grating on the entire area was calibrated. The peak-to-value of the Z-directional out-of-flatness was 120 nm and the standard deviation of the calibration result was 5 nm over the entire area, respectably. The Z-directional out-of-flatness of the XY grating is caused by fabrication condition of the grating and out-of-flatness of the substrate before fabricating the grating. The X- and Y-directional period deviations of the XY grating were also presented over the entire area. The fabricated XY grating had the X-directional period deviation of 122 nm (PV) and the Y-directional period deviation of 142 nm (PV), respectably. It was caused by environmental influences during the fabrication of the XY grating such as un-uniform fringe condition by the vibration, the refractive index of the air by the temperature change.

In chapter 3, the measurement errors of the self-calibrated diffraction grating in Chapter 2 were analyzed by evaluating the form error of the reference mirror in the Fizeau interferometer and the influence of the inclination angle. The form error of the reference mirror of the Fizeau interferometer was evaluated by processing not only the X- and Y-directional positive and negative first-order interference signals generated from X- and Y-directional positive and negative first-order diffraction beams by the diffraction grating. After that, the influences on the cosine error components generated by the inclination angles with respect to the X- and Y-axis in the measurement results were also evaluated. A commercial Fizeau interferometer, which had the wavelength of the 632.8 nm, was used in the experiment. A reflective-type diffraction grating was set to the tilt stage under the Fizeau interferometer. The vertical resolution of the Fizeau interferometer is 0.05 nm. The lateral resolutions in the XY-axes were 300 m, which determines the measurement intervals of both the wavefronts of the diffracted beams from the XY grating and the reflected beams from the reference mirror in the Fizeau interferometer. An XY grating, which was fabricated with the pattern pitch of 1 m in the area of 100 mm × 100 mm, was employed as a measurement target. The form error of the reference mirror calculated from the phase outputs of not only the X- and Y-directional positive and negative first-order diffraction beams but also Z-directional zeros-order diffraction beam. The difference was about ±10 nm in the area of 100 mm × 100 mm. It was confirmed that the acquired form error of the reference mirror well agreed with each other. It should be noted that each profile showed a peak-to-valley value of about 27 nm, which is within the specification of the Fizeau interferometer (λ/20) but is not negligible for further more precise evaluation of the XY grating. The influence by the inclination angles were also discussed by comparing with the period deviations with the form errors by the inclination angles with respect to the X- and Y-axis including the phased outputs of the X- and Y-directional positive and negative first-order diffraction beams. Because the inclination angles affect to the measurement results of the X-directional period deviation as the cosine errors, it should be evaluated to improve the measurement accuracy of the X-directional period deviation.

Chapter 4 describes the 3-axis grating interferometric vibrometer using 2-dimensional XY grating with a grating period of 1 μm was developed to detect of the XYZ-axes vibrations and its basic performances were evaluated. It was confirmed that the prototype two-axis linear encoder can measure the displacements with the resolution better than 0.5 nm. The measurement errors within the short measurement range were dominated mainly by the interpolation errors of the quadrature interference signals and the slope components, which were caused by the misalignments of the components in the optical sensor head and the setting errors of the sensor system. The 3-axis vibrations of the linear air-bearing stage were also investigated by applying the proposed 3-axis grating- interferometric vibrometer.

In Chapter 5, two types of the mosaic encoders were developed and their basic performances were evaluated. Firstly, the mosaic encoder with optical probes (Probe I, Probe II) for enlarging the measurement range of the 1-axis linear stage was developed. The mosaic XY grating with a grating period of 1 m, which was constructed by assembling the XY grating by the light lithography based on two beams interference along the moving axis of the stage, were proposed. The gap between two XY gratings was set to be 1 mm. The mosaic encoder for the mosaic XY grating with a grating period of 1 m was also constructed. The mosaic encoder for 1-axis linear stage could measure the XYZ-directional displacements. The resolutions with respect to the XYZ-axes were 1 nm. By switching the signals from two probes, the displacement of the gap could be measured when the two probes were scanned on the gap of the mosaic XY grating. To measure the large area with respect to XY-directional displacements of the planar stage, the new mosaic encoder was also proposed, which had four probes (Probe A, Probe B, Probe C and Probe D) composed by optical layout. The X-directional displacements by four optical probes of the new

In Chapter 6, the achievements of this thesis are concluded.

論文審査結果の要旨

近年，精密ステージの位置決め特性評価またはフィードバック制御のために，回折格子を用いた光学式エンコーダが使われている。光学式エンコーダ内で測定基準として用いられる回折格子のピッチ偏差と平面度誤差は，エンコーダの測定精度に影響するため，その評価が重要な課題となっている。さらに，ステージの高精度位置決めのための多軸変位計測の必要性が高まっている。本論文は，回折格子からの回折光を積極的に利用することで回折格子のピッチ偏差及び平面度誤差を評価し自律的に校正する手法の開発，及びその応用として提案する多軸変位検出原理の開発についてまとめたものであり，全編 6 章からなる。

第1章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，回折格子のピッチ偏差と平面度誤差（格子エラー）を評価するための，光学式フィゾー干渉計を用いた自律校正法の開発について述べている。回折格子面に測定光を入射した際に発生する 0 次光および±1 次回折光と，参照光との干渉によって得られる 2 次元干渉パターンを用いる校正アルゴリズムを新たに提案している。開発の手法は，回折格子のピッチ偏差と格子エラーを自律的に，かつ分離しての評価が可能であり，その学術的価値が高い。また，測定基準を利用する従来型の評価法に比べて高速かつ高精度な測定を実現しており，その産業的価値も高い。

第3章では，第2章で開発した自律校正手法の測定精度を向上する手法の開発について述べている。測定に用いるフィゾー干渉計の参照ミラー平面度を，回折格子を用いて自律的に評価する新アルゴリズムを開発し，当該フィゾー干渉計の参照ミラーが PV 値 27 nm の平面度誤差を有していることを実験的に明らかにしている。さらに，この新アルゴリズムで評価した参照ミラーの平面度データを第 2 章で開発した自律校正法に反映することに成功している。これは，回折格子の自律校正法を高精度化する上で重要な成果である。

第4章では，校正した回折格子の応用として，ステージの 3 軸振動を一括計測するための回折光干渉型 3 軸変位計測システムを提案している。前章までに開発の手法で校正した回折格子を用いて試作した計測システムが，各軸サブナノメートルの変位検出分解能を有することを確認している。さらに，試作したセンサの計測特性を精密位置決めステージ上で評価し，ナノメートルレベルの 3 軸変位計測が実現できることを実証している。これらの結果は，提案した多軸変位検出原理の有効性を示すとともに，ステージの 3軸振動特性を評価する新たなアプローチを提案するものであり，重要な成果である。

第5章では，位置決めステージの大面積位置検出に向けた回折格子の応用法について述べている。第4章で提案の多軸変位検出原理について，複数の回折格子をつなぎ合わせて計測範囲拡大を試みるコンセプトを提案している。回折格子つなぎ合わせの際に発生する問題を解決するため，光源にマルチプローブを採用したセンサヘッド光学系を新たに開発し，基礎実験の結果からその有効性を実証している。これは，提案の多軸変位検出原理を実用化するにあたり，有益な成果である。

第6章は，結論である。

以上要するに本論文は，回折格子のピッチ偏差及び平面度誤差を分離して評価する自律校正手法と，これにより校正した回折格子を応用した多軸変位検出原理を新たに提案するとともに，その実現可能性を実験的に実証したもので，学術的に新規性があり，かつ産業的にも有用な計測範囲拡大のコンセプトを新たに提案している点からも，ナノメカニクスおよび精密工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。